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TITLE: BASIC PHYSICS PROGRAM FOR A LOW ENERGY ANTIPROTON SOURCE IN NORTH AMERICA*

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Basic Physics Program For A Low Energy Antiproton Source In North America*

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ABSTRACT

We summarize much of the important science that could be learned at a North American low energy antiproton source. It is striking that there is such a diverse and multidisciplinary program that would be amenable to exploration. Spanning the range from high energy particle physics to nuclear physics, atomic physics, and condensed matter physics, the program promises to offer many new insights into these disparate branches of science. It is abundantly clear that the scientific case for rapidly proceeding towards such a capability in North America is both alluring and strong.

CONTENTS

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I. INTRODUCTION AND OVERVIEW

During the past few years there have been numerous workshops and conferences devoted to the science under discussion here. In particular one should mention the series of LEAR workshops[1,2] the Madison workshop[3] on the Design of a Low Energy Antimatter Facility, and the Fermilab workshop[4] on AntiMatter Physics at Low Energy (AMPLE) In the present article, we extract what appears to be the most compelling of the wide variety of physics that would become accessible, and attempt to give sufficient details to allow one to judge the basic physics case for such a machine

The guidelines issued for the present workshop indicated a somewhat arbitrary 200 MeV maximum energy for the machine under discussion The limitations thus imposed on the diversity of physics by such a ceiling, while certainly considerable, will be seen to be far from devastating Missing from the agenda of such a machine would be the very intgeresting higher energy topics such as the $\Delta S=1$ CP violation experiment[5], $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$, the new measurements that could be done in charmonium spectroscopy[6], and the puzzle[7] of the enormous deviation from QCD predictions of the ratios for the branching fractions of the J/ψ and the ψ' to exclusive final states We include a brief discussion of the first and last of these in Section VIII under the "Higher energy $\bar{p}$'s" heading

As emphasized by Bob Jaffe[6] in the Fermilab Proceedings, there are two broad areas of concern in particle physics today These can be described as the "Origins of the Standard Model" and the "Dynamics of

Confinement in QCD[7] It is remarkable that a low energy antiproton facility such as the one under consideration here can address both these questions in a vital and straightforward manner

While it is true that the standard model has enjoyed considerable success, it is less frequently mentioned, but no less true, that there are many parameters and phenomena that are arbitrary and not understood. Examples are i) the sources of weak symmetry breakdown, ii) the origin of CP violation, iii) the origin of quark and lepton masses and angles, and iv) even why SU(3)xSU(2)xU(1) should be the fundamental gauge groups chosen by nature. In fact, the absence of proton decay at the 10^{32} year lifetime has cast serious doubt on this simplest version of the standard model A low energy antiproton machine will contribute to our understanding in this area most directly through precision tests of various invariance principles such as CP, CPT, and T Therefore, this topic forms one of the cornerstones of the basic physics program for the facility

The theory of Quantum Chromodynamics has also had its many successes However, after more than a decade, many fundamental questions are still unanswered The nature and origin of confinement is still mysterious, the fact that the rich spectrum of particles can be reproduced by naive bag models is astonishing The absence (so far) of definitive evidence for states[8] of gluons (≡G) and/or gluons and quarks may turn out to be fundamental, and yet the large number of particles that have been reported which do not fit into the accepted scheme portends excitement ahead In the field of meson spectroscopy, a low energy antiproton machine can be used to provide high statistics measurements of exclusive final states resulting from $\bar{p}p$ and $\bar{p}n$ annihilations to enable definitive determinations of possible new states.

The various processes which occur when antiprotons annihilate in nuclei offer a rich milieu for uncovering unanticipated phenomena. There have been many speculations and even some calculations[9] concerning the energy densities to be expected when $\bar{p}$'s are absorbed in nuclei Using a reasonable model for the hadronization process. Gibbs and Strottman find that energy densities in the very interesting range of 2 GeV/fm^3 for periods of about 2 fm/c should be attainable Under such conditions we would expect to observe the change of state of nuclear matter to that which is often referred to as "quark-gluon plasma".

A fundamental experiment[10] that has yet to be done is the measurement of the gravitational force on antimatter - the determination of $g(\bar{p})$ Modern theories of gravity predict that the acceleration of protons and antiprotons in the earth's gravitational field will be different[11] The difference arises in quantum theories of gravity which have massive partners of the tensor graviton as carriers of the force of gravity Note especially that this prediction remains regardless of the results from the raft of current experiments searching for anomalous gravitational attraction between matter and matter A program of experiments with antiprotons to determine the strengths and ranges of these additional components to the gravitational force will be an important activity at a low energy $\bar{p}$ facility

A variety of precision tests of CPT could be done given a source of antihydrogen atoms One can envision a measurement of the Lamb shift in

$\overline{H}^0$ for instance. In addition, precision measurements of the gravitational properties of antimatter may well become feasible if sources of $\overline{H}^0$ were to become available. Conti and Rich[12] have given estimates of what is achievable using reasonable extensions of presently existing positron sources.

In the remainder of this paper, we summarize the present status of these and some other topics as they relate to low energy antiprotons. In Section IX, we provide a table of characteristics of some of the most interesting of the experiments discussed here; the number of antiprotons required to perform these experiments is also included there.

II. TESTS OF INVARIANCE PRINCIPLES: CP, CPT, AND T

The role of precision tests of invariance principles in uncovering new and unexpected aspects of physical laws as manifest in the different fundamental interactions has a long and fruitful history. Violations of discrete symmetries often herald either a new interaction or subtle modifications to that which has been presumed known. It is fitting that enormous experimental effort continues to be devoted to the search for and ever more precise measurement of the invariance of the interactions to different combinations of the operations of Charge Conjugation (C ≡ interchange of particle ↔ antiparticle), Parity Inversion (P ≡ $\mathbf{r} \rightarrow -\mathbf{r}$) and Time Reversal (T ≡ $t \rightarrow -t$). Modern quantum field theories make the assumption that all physical laws are invariant under the combined operations of CPT. The discovery of CP violation in the neutral kaon system some 23 years ago has been remarkable because of its uniqueness - it has not been observed in any other system (see also Section VIII A) The combination of CPT invariance and CP violation implies T violation: it has yet to be experimentally verified. As usual, low energy antiprotons offer an important tool for the study of CPT, CP, and T invariance

The elegant and precise demonstration of CPT invariance in the lepton sector has been accomplished by Dehmelt[13] and colleagues over the past quarter of a century They have shown the equality of the <u>inertial</u> masses and the magnetic moments for electrons and positrons isolated in Penning traps. This tests the invariance of the electromagnetic interaction under the CPT operation The technique will be applied to the proton - antiproton inertial mass determination[14] in a LEAR experiment, PS196 The aim is to test the equality of the masses at a level of 10^{-9}, a great improvement over the current precision of 10^{-4} in the hadron sector This will provide a test of the strong interaction under CPT If one could compare the gyromagnetic moments of the proton and antiproton, this would test CPT in both the electromagnetic <u>and</u> strong interactions since the anomalous moments have a complicated source Other tests of CPT in the electromagnetic interaction come with the study of antihydrogen, discussed in Section V.

In the classic experiments studying CP violation, one examines the 2π and 3π decay modes of the neutral kaon systems, K_L and K_S The fact that these are mixtures of the K^0 and $\overline{K}^0$ leads to interference patterns from which on can extract the CP violation parameters ϵ, ϵ', η_{00}, and η_{+-}

It has been emphasized by many authors[6,15,16] that $\bar{p}p$ annihilation offers the possibility of producing tagged K^0 and $\bar{K}^0$ initial states. The study of the evolution of these pure states would allow a measurement of the CP parameters in an experiment having very different sources of systematic errors from the usual K_L-K_S experiments. LEAR experiment PS195 has as its goal the study of the 2π and 3π decays of the neutral kaons (CP) as well as testing the equality of the following reaction rates[17,18,19] (a direct test of T-invariance):

$$\bar{p}p \rightarrow K^- \pi^+ K^0 \;,\; K^0 \rightarrow \bar{K}^0 \rightarrow \pi^+ e^- \bar{\nu}_e$$

$$\bar{p}p \rightarrow K^+ \pi^- \bar{K}^0 \;,\; \bar{K}^0 \rightarrow K^0 \rightarrow \pi^- e^+ \nu_e$$

Anticipated precision for the experiment is comparable to or slightly better than the current value for $|\epsilon'/\epsilon|$, and the first time observation of T violation. A more definitive experiment will require a greater number of antiprotons than can be obtained at LEAR.

We emphasize that the study of CP violation in K meson systems has recently assumed added importance. Just a few months ago, the UA1 group at CERN unexpectedly observed large mixing in the $B^0{}_s\bar{B}^0{}_s$ system[20]. This may mean that there is now a new system in which one can study CP violation, although at a cost that would be be astronomical compared to the machine under consideration at this workshop. Indeed, the CP violation in the $B^0{}_s\bar{B}^0{}_s$ system should be related to that of the K^0 system. It is, therefore, essential to obtain as accurate and complete a parametrization of the K^0 system as possible, as a tool for trying to obtain a fundamental understanding of CP violation (its origin rather than the phenomenological Kobayashi - Maskawa parametrization we have now).

Another experiment that was discussed by J Miller at this workshop is the interference pattern in the 2γ decay of the K_L-K_S system as a new and independent means of observing CP violation Tagged neutral kaons produced by another order of magnitude increase in the number of antiprotons presently available would be essential for the success of such an experiment.

We observe that the equality of the lifetimes of the neutron and the antineutron is a test of CPT in the weak interaction One should consider whether such an experiment would be useful at a low-energy $\bar{p}$ source

III. GRAVITY AND $\bar{p}$'s: $g(\bar{p})/g(H^-)$

Our standard ideas of gravity are really an interesting mixture of classical and quantum physics The weak equivalence principle tells us that the inertial mass is equal to the gravitational mass:

$$m_I = m_G$$

The inertial mass is a kinematic quantity: it is the one which enters in Newton's law of force

$$F = m_I a$$

On the other hand the gravitational mass is the gravitational analog of a charge in electromagnetism It is the quantity which enters in Newton's law of gravitation

$$F = -G\, m_G\, m'_G \;\; r^2$$

The principle of the invariance of the laws of physics under the combined operations of CPT tells us that the inertial mass of a particle is equal to the inertial mass of the antiparticle:

$$m_I = \overline{m}_I$$

From this and Eq. (1) one might make the assumption that

$$m_G = m_I = \overline{m}_I = \overline{m}_G$$

This would be unwarranted, however, because of the aforementioned observation that m_G is the equivalent of a charge. The fact that the ***gravitational*** mass of a particle and its antiparticle are not equal does **not** violate CPT. The principle of CPT dictates that an antiapple falls toward an antiearth in the same manner in which an apple falls toward the earth. It is silent concerning the trajectory of an antiapple (read antiproton) toward the earth. Arguments along this line led to an approved experiment[10] (LEAR PS200) to make this fundamental measurement.

In fact, modern attempts to unify gravity with other forces of nature lead to the generic conclusion[11] that the gravitational acceleration of the antiproton will not be equal to that of the proton, at some level. At present, these theories are hoped to be renormalizable or finite; they do violate the weak equivalence principle and predict effects that are non-Newtonian. One can mention several of the physical motivations: supersymmetry, dimensional reduction, string theory. The literature concerning this subject is now outrageously large, and growing exponentially.

The fact that none of these theories has yet been proven to be mathematically consistent deters no one. Additionally, the apparent lack of any hope to confront these theories with experiment, such as verifying a particle spectrum, leads to a healthy skepticism concerning their connection with the perceived reality. But they are tantalizing, indeed, they may be giving a hint into what the true physics might be. It is likely that the experiment concerning the gravitational acceleration of an antiproton in the earth's field may bear on this subject.

These modern theories of gravity have many common features. They have spin = 1 and = 0 partners of the graviton, which may couple in a generation-independent way to fermions, and in addition have finite ranges. What phenomenological effects are implied by these new particles? By considering a linearized theory and ignoring relativistic effects, we obtain the following form for a gravitational potential.

$$V(r) = [-Gm_1 m_2/r]\ [1 \pm ae^{-r/v} + be^{-r/s}]$$

(See reference 11 for the complete treatment including the other effects.) The first term, the normal tensor gravity term, is followed by two new non-Newtonian terms. The vector term has a $\pm$ associated with it, a relative coupling constant, a, and a range, v. The scalar term has a relative coupling constant b and range s. (The ranges are the inverse masses of the graviphoton and graviscalar in appropriate units.)

The minus sign in front of the vector term would correspond to matter repelling matter. This is mathematically the same as the vector photon of electromagnetism: like charges repel. On the other hand, opposite charges (antimatter and matter) attract. The plus sign describes this situation.

One naively expects a and b to be of gravitational strength (In principle, there could be many components, we parametrize all these as being summed up to be a and b.) Thus, if a and b are of equal magnitude, then for matter-matter interactions the vector and scalar terms would almost cancel. One might observe an effect only in very precise matter - matter experiments. However, for antimatter - matter interactions, the sign in front of the vector term is opposite, and the vector and scalar terms add together. The antimatter - matter interaction displays a new first order effect. In addition, the matter - matter interaction gains a new, second order effect.

The size of the effect depends upon the value of the parameters mentioned above. If these new effects are on the Planck scale, 10^{-33} cm, then they can be considered to be unobservable. If, however, they are on the 200 meter scale, which the "fifth force" advocates would like, then although the effect would be present it would be undetectable in the approved antiproton experiment. However, if it's on a longer scale, then indeed an effect will be measured.

What size of effect could one have? Stacey, Tuck, and Moore[21] have done an analysis of the Australian mine data, using both the new vector and a scalar term. They find (a - b) = 0.01, and allowed ranges up to ~450 km. This result has been put into the PREM model of the earth and integrated to see what effect would be anticipated for the antiproton gravity experiment.[10] The calculated results on the variation of g, as a function of the (set to be equal) ranges, show surprisingly large effects for ranges greater than several kilometers. In particular, for ranges of 40 km. one calculates a 1% effect in the antiproton experiment which should be measureable At 450 km one would have a 14% effect. definitely measureable This is for $a=b=1$. the effect scales with the value of $a(=b)$

If you add to this the analysis of rapidly-rotating pulsars. which allows values of (a,b) up to $O(100)$. then the expected difference in g for the antiproton could be

$$\Delta g/g = 0.14 \cdot a \cdot v / 450\text{km}.$$

The details of the experiment are given elsewhere.[10] Simply stated. antiprotons from LEAR will be decelerated in several stages by the use of degrading foils and Penning traps. eventually cooling them down to approximately 10 K They will then be tossed up a superconducting drift tube: the cutoff in the arrival time spectrum will provide a measurement of g More accurately. the comparison between antiprotons and H^- will allow this to be extracted

Of course. the ultimate gravitational experiment concerning antimatter would be done with neutral antihydrogen The advent of laser storage and velocity selection techniques for single atoms and magnetic trap devices may eventually open up the possibility for such an experiment

IV. ANTIPROTON ANNIHILATION IN NUCLEI

Under what conditions might we expect to form a "quark-gluon plasma" (QGP)? For a start we believe that a state of quarks and uons exists inside a nucleon Givc a nucleon radius of 0 8 fm. the matter density ρ.

is about 0.5 GeV/fm^3. For a radius of 0.6 fm, $\rho \approx 1$ GeV/fm^3. It seems reasonable to expect that if we can arrange to obtain a density of 1 to 2 GeV/fm^3 over a <u>nuclear</u> volume, we just might observe a change of phase to the long heralded QGP. This region represents an increase in mass density to $\rho / \rho_0 = 6$ times normal nuclear matter density at normal nuclear temperature, or equivalently a temperature of 180 to 200 MeV at normal density. Heavy ion collisions probe the high density-low temperature region whereas energetic $\bar{p}$ - Nucleus collisions may well provide a means to explore the "low" density-high temperature region of the nuclear matter phase diagram.

Qualitative arguments about what incident $\bar{p}$ momentum would maximize the temperature inside the nucleus proceed along the following lines: slow $\bar{p}$'s annihilate on the surface because of the very large total cross section, the energy quickly escapes the nucleus. At higher $\bar{p}$ energies the annihilation takes place about a fermi inside the nucleus. The annihilation pions, numbering about ten, move mostly forward in the lab frame and have a high probability of depositing their energy in a small part of the nuclear volume through collisions with several ($\approx$5) of the constituent nucleons.

Motivated by such qualitative considerations, Gibbs and Strottman[9] performed calculations using the Intranuclear Cascade (INC) formalism. Their results show that for 6 and 8 GeV/c antiprotons absorbed on an A=100 nucleus, the temperature attains the 180 MeV value where a phase transition is predicted. They also calculate the total amount of energy that is actually absorbed in the nucleus. For 8 GeV/c $\bar{p}$'s, 6 GeV gets absorbed Thus the process is very efficient for putting the energy where it is desired - in the nucleus The calculated nuclear densities that are attained during the excursion into the high temperature domain are modest: $\rho / \rho_0 \approx 1.4$ to 1.8. It is this result that leads to the conclusion that energetic $\bar{p}$ absorption on nuclei provides an alternate route towards a quark-gluon plasma It complements the more widely discussed relativistic heavy ion collision technique since it utilizes high T - low ρ instead of the converse

For a long time the role of strangeness production as a key signature of QGP formation has been emphasized Close examination of data from a bygone era has led Rafelski[22] to conclude that high nuclear temperatures (>100 MeV) have been observed in at least three experiments.

1) $\bar{p}\, d \rightarrow (p_{spectator})\, K\, \bar{K}\, \pi$'s at 1 - 3 GeV/c

2) $\bar{p}\ {}^{238}U \rightarrow$ neutron with the $\bar{p}$ absorbed at rest, and

3) $\bar{p}\ {}^{181}Ta \rightarrow \Lambda, K_s$ at 4 GeV/c

These are discussed in some detail in the article by G A Smith in the present proceedings The conclusion can only be that the opportunities for new discoveries here are excellent

V. ANTIHYDROGEN AND BASIC PHYSICS TESTS.

The formation and control of antihydrogen would represent both a technological triumph and a golden opportunity Methods of obtaining this exotic atom have been studied by several groups[12,23,24,25] Once such an atom is obtained, it will be a veritible CPT laboratory for making fundamental physics tests of quantum electrodynamics. Finally, this would set the stage for the even more demanding project of storing possibly macroscopic quantities of antihydrogen in the form of cluster ions. We examine in more detail these three separate stages of scientific development which would become accessible to study at a North American antiproton source.

A. ANTIHYDROGEN FORMATION

Antihydrogen is composed of the antiparticles of the constituents of hydrogen, viz. an antiproton orbited by a positron. Since both these particles have separately been captured and controlled at low energies in ion traps, it is apparent that the next step is the formation, then control of antihydrogen from these entities.

The first effort in this direction is the proposal[27] to merge beams of positrons and antiprotons at LEAR, and observe the following reaction

$$\bar{p}\, e^{+} \rightarrow \bar{H}\, \gamma,$$

that is, the radiative formation of antihydrogen. To boost the rate of formation of the atom, the CERN group considered using a pulsed dye laser to stimulate capture of positrons to the n = 2 Bohr orbit. They calculate that they could produce an antihydrogen atom every few seconds using this technique.

An experiment using normal matter is planned at the University of Western Ontario.[25] Using the existing apparatus of the Merged Electron

Ion Beam Experiment. protons and electrons will undergo stimulated radiative recombination to yield experimental results which bear directly on the CERN experiment As a further step. Rich, et al.[27] have proposed using a storage ring to contain the positrons, which should enhance the rate considerably

Another approach circumvents the necessity of having the relative velocity of the antiproton and positron being so precisely matched Antiprotons collide with positronium and form antihydrogen in the following reaction

$$\bar{p} + (e^{-}e^{+}) \rightarrow \bar{H} + e^{-}.$$

In the Aarhus collaboration.[23] the idea is to have a beam of antiprotons going through a hollow cylinder of aluminum A separate beam of positrons enters through a hole in the cylinder, strikes the inside wall, and forms positronium The first experiment would expect on the order of one antihydrogen atom per second, with dramatic increases foreseen after more work

The above techniques would produce relatively fast antihyhdrogen Colder antihydrogen would come from creation in traps One should be able to store 10^{10} charged particles per cm^3 in traps at 10 K This led to the suggestion[28] of a pair of nested ion traps each containing such numbers of positrons and antiprotons Scenarios were envisioned wherein these particles could be induced to combine in very short times A complete discussion of these ideas is contained in the article by Mitchell in these Proceedings

B. BASIC PHYSICS TESTS

After successfully creating antihydrogen, the problem of containment and control becomes imperative, since it is neutral. A natural choice is a magnetic trap[29]. Single atoms might be so contained given an appropriate laser to control their velocity. In fact, this may well be the most precise method that one could devise for measuring the gravitational attraction of antimatter to the earth.

Experiments that would become immediately possible would concentrate on study of the antihydrogen atoms before their ultimate fate of annihilation. Poth[30] has emphasized the opportunities offered in atomic and strong interaction physics by studies of antiprotonic and hyperonic atoms. The most obvious fundamental measurements that would be made with antihydrogen, however, would be the tests of CPT for Quantum Electrodynamics.

As discussed in detail in the article by Nieto in these Proceedings, the CPT theorem states that for a given interaction, any measurement made with hydrogen - magnetic moment, transition amplitudes, decay rates, energy levels, energy shifts - would have the analogous quantity in antihydrogen exactly predicted by CPT. The antihydrogen atom would thus allow tests of CPT to be made for the entire set of measurements which form the basis of QED, as we know it, for the hydrogen atom.

C. CLUSTER IONS

The final topic in this section concerns the formation of cluster ions of antimatter. As Stwalley discusses in these Proceedings, the concept is daunting, but challenging. A cluster ion, denoted by H_N^+, is an ion composed of N hydrogen atoms with one electron removed, leaving it with a single positive charge. In this case it reduces simply to N protons and (N-1) electrons.

Ultimately what would be desired is to form a very large "seed crystal" consisting of N antihydrogens. This could conceivably then be augmented, a single atom of antihydrogen at a time. Obviously, one can examine the feasibility of this scheme by using ordinary hydrogen. One possible path is to first form H_2^+ by indirect radiative association

$$H^+ + H + \gamma \rightarrow H_2^{+*} \rightarrow H_2^+ + \gamma$$

or associative ionization

$$H^* + H \rightarrow H_2^+ + e^-$$

Laser-assisted association could be used to make H_3^+ from H_2^+ and H. In principle, one could continue this process to high N, but this involves a complicated knowledge of the spectroscopy for each species. A series of three body interactions may be preferable at this stage.

It is a fortunate circumstance that all these complicated, unknown aspects of cluster ions can be studied with normal matter first. The transition to antimatter will require that the techniques evolved for matter ensure that in the antimatter case, no antimatter comes in contact with matter, because of the added complication of annihilation. Stwalley covers this aspect of the problem in some detail.

VI. MESON SPECTROSCOPY.

Meson spectroscopy has reached an exciting stage. A variety of experiments find evidence for resonances which do not fit into the standard pattern of $\bar{q}q$ meson nonets. A current table of exotic results which updates Ref. 8 has been prepared by Sharpe and is given here as Table I. Eleven "confirmed oddities" are listed. Good reasons are given in in the paper by Sharpe in these Proceedings [ ] as to just why none of them fit neatly into our current framework of $\bar{q}q$ nonets. These states could well represent the opening up of a threshold of exotic meson resonances - those which contain constituent gluons.

Such exotic mesons have long been expected in the spectrum of QCD. This follows from an extrapolation of models which can account for the standard pattern of meson nonets, e.g. the MIT bag model or the flux tube model. These models suggest that in addition to q and $\bar{q}$ constituents, there should be independent excitations of gluons - constituent gluons (g). If so, there will be new resonances: glueballs (G≡gg) and meiktons or hybrids ($\bar{q}qg$). Some of these states have exotic quantum numbers which are not available to $\bar{q}q$ states, e.g. $J^{PC}=1^{-+}$. We shall refer to all such states as exotic mesons.

It has not yet been proved theoretically, however, that such exotics exist in the spectrum of QCD. Eventually, numerical lattice calculations

TABLE I. Exotic Results in Meson Spectroscopy*

$J^{PC}=0^{+-}, 1^{++}, 1^{+-}$ $\overline{q}q$ nonets filled.
Confirmed oddities are listed here.

Conjectured Structure	Particle Name	J^{PC}	Isospin	Mode of Study with $\overline{p}$ source
G, $\overline{q}q$	η or $\iota(1460)$	0^{-+}	0	$\overline{p}p$ at rest
$\overline{q}qg$	f_1 or E(1420)	1^{++} (1^{-+})	0	"
G, $\overline{q}q$	f_0 or G(1590)	0^{++}	0	"
$\overline{q}qg$	ρ' or C(1400)	1^{--}	1	"
$\overline{q}^2q^2$	X(1480)	0^{++}or 2^{++}?		"
G	f_2' or $\theta(1720)$	2^{++}	0	$\overline{p}p$ in flight
$\overline{q}qg$, $\overline{q}q$	$\xi(2200)$	2^{++} or 4^{++}	0	"
G	$\varphi\varphi$ (3 states~2200)	2^{++}	0	"
$\overline{q}q$	$\varphi\varphi$ (2200)	0^{-+}	0	"

*Table prepared by S. Sharpe, see his article in these Proceedings.
Data from LASS (Kp), MKIII, TPC/MKII, Lepton-F, BNL, MPS, ...
G=gluons.
In no case is interpretation unambiguous.
Need more decay channels--Need more data.

may be able to answer this question from first principles and provide predictions for the masses of the lightest exotics Until then progress can only come from experiments searching for exotic states, measuring their properties and comparing the experimental results with model predictions ... can then decide between phenomenological models, which in turn will ... e better theoretical input to experiment The goal is eventually to ... both the model and the data it reproduces to the calculations based on first principles In this way we achieve a quantitative test of QCD, while at the same time obtaining useful phenomenological models for the spectrum of field theories. These can in turn be applied to future theories of matter at shorter distances

A high luminosity, low energy $\bar{p}$ source can play a central role in such a program Annihilations at rest enable a detailed study of exotic mesons with masses up to ~1 7 Gev, while annihilations in flight can extend this range up to and beyond the ψ Present models all suggest that the threshold for exotic mesons lies below 1 7 GeV and that the number of states increases rapidly with energy Decay widths increase with increasing mass, so the spectrum can probably only be unravelled for about 1 GeV above threshold Thus a low energy $\bar{p}$ source will provide a window through which one hopes to view this exotic landscape.

It should be emphasized that a successful search for such states will, of necessity, utilize every known experimental trick one can muster A good example is quantum number restriction of final states, which helps to reduce the inevitable backgrounds from conventional mesons When antiprotons annihilate at rest in liquid hydrogen, Stark mixing causes practically every annihilation to proceed from an initial L=0 state. For particular final states, e. g. $\eta\pi^0\pi^0$, $\eta\eta\pi^0$, $\varphi\pi^0\pi^0$, this can be especially powerful. Because the branching ratios for such channels are expected to be small, probably in the range 10^{-4} to 10^{-5}, high luminosity will be essential for these measurements.

Another potent experimental strategy is to use the fact that a $\bar{p}$ machine of several GeV/c represents a real ψ factory. It has long been recognized that the most promising way to find unambiguous evidence for glueballs is in the radiative ψ decays: $\psi \to \gamma X$. In this case X can be a digluon in a color singlet. By using realistic $\bar{p}$ machine parameters of: a) momentum resolution of a few times 10^{-5} (e^- cooling, gas jet target), and b) luminosity of 10^{31} $cm^{-2} \cdot sec^{-1}$ (current technology), then one obtains[31] the astonishing estimate of 10^9 ψ's produced per year! This is hundreds of times as many ψ's as have been produced so far in all the e^+e^- collider experiments to date. The two big advantages offered by a $\bar{p}$ machine are as follows: a) luminosity - 10^{31} cf. 10^{29} for e^+e^- machines, and b) very small momentum spread - $\Delta\sqrt{s}/\Gamma_\psi$ is less than one for $\bar{p}p$, cf. ≈ 100 for e^+e^- machines. The fact that much hadronic background accompanies the desired process in the $\bar{p}$ case is an inconvenience that can be managed by modern fast triggering techniques.

VII. <u>ANTIMATTER STORAGE IN NORMAL MATTER</u>

The ability to store antimatter in matter will probably be required if we are to realize the dream of using antimatter in large-scale practical applications. On the way towards that goal lies an array of solid state physics studies of much interest. Assuming, for example, that a source of antiprotons exists with the appropriate deceleration facilities to make them available at low energies, the question that is addressed by L. Campbell in these Proceedings is as follows: just how many of these antiprotons can be stored by which techniques.[1]

The "standard" ways of storing antimatter are in electromagnetic bottles, such an Penning traps. In the section on antihydrogen, we mentioned the possibility of storing an antihydrogen atom in a magnetic bottle; while very interesting for many experimental purposes, it is of limited utility for dense antimatter storage. (The possibility of electromagnetic levitation of solids is skipped here.) In order to store significant amounts of antimatter, new technologies will have to be invented.

One technology could involve direct storage of antiprotons in condensed matter because the electromagnetic force, which prevails there in astonishing complexity, has a much longer range than the strong force which is responsible for the ultimate fate of annihilation of the antiproton. However, an equally important feature of stable condensed matter, Fermi statistics, discourages hope for equilibrium trapping of antiprotons. Nevertheless, the combination of effects like dynamic stabilization and special environments such as the surface of superfluid ^4He may lead to environments that locally trap antiprotons. Even small-scale surface storage would be quite valuable as a nucleation site for antihydrogen cluster ion formation by providing a mechanism for efficiently conducting the condensation energy to normal matter.

An even longer term version of this question applies to the possibility of neutralizing antiprotons with positrons to produce antihydrogen. Then one would want to know how to store this even more interesting yet difficult to handle species. The interesting chemistry and physics problems associated with this are discussed by Stwalley in these Proceedings.

The basic problem in storage can be understood in the context of Lieb's theorems[32] on the absolute stability of matter. Lieb has shown that the stability of large-scale matter is due ultimately to the Pauli exclusion principle. However, there is **no** Pauli exclusion principle operating between matter and antimatter, so there is nothing *a priori* to prevent their coming together, and hence annihilating. Thus, one is forced to try to avoid the implications of Lieb's theorems.

For charged particles, containment by some configuration of static electric fields is forbidden by Earnshaw's theorem. There are, however, promising avenues to explore in steady-state, nonequilibrium systems (such as storage rings) or those systems in which the decay constant of the instability is long (as in some traps utilizing combinations of electric and magnetic fields). As an obvious first step, one might consider the miniaturization of electromagnetic traps. As Campbell discusses in these Proceedings, existing traps can, in principle, be scaled down in size to the order of 10^{-4} cm, with the consequent maximum densities of order $10^{13}/cm^3$. Thus, Campbell can "envisage" a cubic meter of these small traps containing, in principle, up to 10^{18} antiprotons.

However, these would still not be atomic - scale traps. Such a trap has been conceived of by Clark, et al.[33] They point out that one could use the "Stark saddle", or force - free location of a particle in an applied external field plus a local ion field. Since this is a saddle, applying a perpendicular magnetic field will only produce metastability, as compared to the stability of a Penning trap. The numbers imply that this concept may be of use in gaseous phase.

There also may be an atomic analog to the storage ring which would make use of the phenomenon of channeling of charged particles in a crystal: the channel ring. This is even more speculative, since it is not known how to fabricate a closed-path channel in a crystal. It is even more difficult to imagine how to arrange a reflection at each end of a straight path. However, one might derive encouragement from the recent, unexpected observation[34] of π^- channeling in a helical pattern around lines of atoms in a crystal.

Campbell has estimated the atomic scale trapping parameters which would prevent a stored antiproton from either annihilating directly or being first captured in an atomic orbit and then annihilating. He finds that such a trap could contain an antiproton for a year if the antiproton is kept a few Ångstroms away from ordinary matter. Muons have similar trapping characteristics in this respect, and so would serve as good test particles in developing such small scale traps. (It is also mentioned that polaron and exciton states centered about antiprotons in solids provide a rich field of study for theorists interested in antiprotons in solids.)

The problem of storage in solids can be approached from an alternative viewpoint: that of understanding the quantum mechanical properties of particles in potential wells. Just how does a particle tunnel and/or decay from a metastable state to a lower state: that is, to annihilation. Various studies have found that:

i) By slightly changing the shape of a potential, one can inhibit tunneling unless there is either coupling to other modes or dissipation in the system.
ii) The exponential decay rate can be modified significantly if the product of the decay itself is unstable.
iii) In certain coupling situations, muons and protons inside solids can change from a diffusive condition to a trapped condition.
iv) A charged particle in a lattice can be localized under the action of a time-dependent electric field.
v) The conditions for localization and/or tunneling in two-level systems have been studied in detail.

Note that the above separate topics and their conclusions are in principle (and sometimes explicitly) related to each other.

All the above ideas suggest that we must rely on experiments to tell us which, if any, of them will yield practical large-scale storage devices. We also note that none of these experiments are presently being done. Although some of the suggestions are admitedly in the "let's see what happens category," this is often the way new phenomena are discovered in the complicated condensed matter world It is instructive to mention the example of high temperature superconductors in this connection

A first particular suggestion is to see if channeling occurs, and how it occurs, with antiprotons Equally interesting is what antiprotons will do in superfluid ^{4}He Some have suggested that "bubbles" or self- contained cavities might occur, as is the case with electrons[35] and positronium[36] Further, there is the possibility that with an applied electric field one can make electron-antiproton states at the surface which do not penetrate the surface (because of the electrons) and thus have a long antiproton annihilation rate.

Three environments where one does not expect long scale trapping to occur are in degenerate liquid ^{3}He, superconductors, and semiconductors However, these are all such interesting and exotic substances, that it is worth performing experiments with antiprotons just as a diognostic tool, let alone for the possible unforeseen surprises that might occur

VIII. HIGHER ENERGY $\bar{p}$'s

A. CP VIOLATION IN $\bar{p}p \to \bar{\Lambda}\Lambda$

It was 23 years ago that CP violation was discovered in the decay of the neutral kaon system ($K^0 \leftrightarrow \bar{K}^0$) In the interim, this puzzling phenomenon has not been observed in any other system than the one in which it was originally discovered The Standard Model has problems accomodating the magnitude of the violation, myriad extensions to the standard model have been proposed

1) the Kobayashi Maskawa Model wherein the violation occurs in the coupling of the gauge bosons to the quarks but is generated by the Higgs sector.

2) the Weinberg Higgs Model where the violation is found in the Higgs potential and is manifest in the coupling of the Higgs to the quarks.

3) the Superweak Model, where again the violation comes from Higgs, but in this model CP violation would be restricted only to the kaon system and

4) the Left - Right Models in which the violation arises from both the effects in 1) and 2)

Whether both $\Delta S=2$ (as in $K^0,\overline{K}^0$) and $\Delta S=1$ (as in $\overline{p}p \rightarrow \overline{\Lambda}\Lambda$) exhibit CP violation would appear to be an experimental question The various models of CP violation differ in their predictions[5] of the magnitude of $\Delta S=1$ $\overline{p}p \rightarrow \overline{\Lambda}\Lambda$ CP violation They all agree, however, that it is sufficiently small as to make the measurement extremely hard

The experimental quantities which are expected to be related to the CP violating phases and thus demonstrate CP violation if found to be non-zero are

$$\Delta = (\Gamma - \overline{\Gamma}) / (\Gamma + \overline{\Gamma})$$

$$C = (\alpha + \overline{\alpha}) / (\alpha - \overline{\alpha})$$

$$B = (\beta + \overline{\beta}) / (\beta - \overline{\beta})$$

Thus Δ measures the difference in the partial decay width for the $\overline{\Lambda}$ and the Λ, C and B reveal differences in the decay parameters which characterize the angular distribution of the decay products of the hyperon and antihyperon. By using the known $\Delta I = 1/2$ rule and final state π-N interaction, Donoghue[5] estimates that the magnitudes of the three quantities are related as follows: $B = 10 \cdot C = 100 \cdot \Delta$. He also finds that the Kobayashi Maskawa Model predicts about $2 \cdot 10^{-5}$ for the value of C, while the Weinberg Higgs Model yields 10^{-4}.

Although a recent LEAR experiment[37] with only 4,000 events found that $C = -0.07 \pm 0.09$, consistent with zero, it is obvious that an improvement in precision by a factor of one to ten thousand is not a trivial matter. One will need to measure accurately the symmetric decays $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$; between 10^8 and 10^9 events in this channel must be collected and analyzed in order to achieve the required level of precision. The number of antiprotons required is very large, on the order of 10^{14} to 10^{15}.

B. EXCLUSIVE CHARMONIUM DECAYS

As a representative example of the broad class of experiments that study exclusive final states in $\bar{p}p$ annihilation, we mention one of the rare "crisply defined experimental puzzles" in high energy physics which would incidentally be amenable to study with a high luminosity $\bar{p}$ source. The evidence for this puzzle has been accumulating for many years. Brodsky, Lepage and Tuan[7] reminded us of its significance in a recent paper.

The decay of the ψ and the ψ' into exclusive final states of hadrons is expected to proceed via three gluons or, occasionally, via a single direct photon. The probability for the decay is proportional to the square of the wave function of the $c\bar{c}$ pair at the origin: $|\Psi(0)|^2$. Thus one would expect that the ratio of the branching fractions for ψ' and ψ to hadrons to be the same as for leptons, namely

$$Q_h \equiv B(\psi' \rightarrow \text{hadrons}) / B(\psi \rightarrow \text{hadrons})$$

$$= B(\psi' \rightarrow e^+e^-) / B(\psi \rightarrow e^+e^-)$$

$$= 0.135 \pm 0.023$$

For a host of final states such as $\bar{p}p\pi^0$, $2\pi^+2\pi^-\pi^0$, $\pi^+\pi^-\omega$, and $3\pi^+3\pi^-\pi^0$, this expectation has been fulfilled. For the $\rho\pi$ and $K^*\bar{K}$ final states, this is not so:

$$Q_{\rho\pi} < 0.0063$$

$$Q_{K^*\bar{K}} < 0.0027.$$

These are upper limits only, thus the ratios are at least a factor of **<u>20</u>** and **<u>50</u>** times smaller than expected. An appealing proposed explanation is that a reasonably narrow intermediate state of gluonium exists close to the ψ mass which then couples to hadrons. In essence this makes the denominator of Q_h larger than expected from QCD arguments alone.

Here is an outstanding example of an experiment that is <u>very</u> difficult without a $\bar{p}$ source (see section VI concerning the efficiency of production of ψ's), but would be relatively straightforward with a machine that would take $\bar{p}$'s up to 7 GeV/c.

IX. SUMMARY AND CONCLUSIONS

The range of physics topics that has been touched on in the present article is indeed vast. The participants in the Basic Physics Program section of the workshop summarized the experimental requirements for most of the topics that were discussed there. Table II gives the results of these requirements. The degree of difficulty, as defined in the footnote to the table, is indicated for a range of experiments, also given is the number of antiprotons that would be required to perform the experiments. As can be seen there, the range covers the map - from just a few antiprotons to more that 10^{14}. As a reference point, we note that LEAR has provided fewer than 10^{13} $\bar{p}$'s in any year of operation[38] up to the present time. We also mention that the CP violation experiment (PS195) has been approved for a total of 10^{13} $\bar{p}$'s, but obviously could use at least another order of magnitude in order to do a good measurement of $|\epsilon'/\epsilon|$.

There was much discussion at the workshop about the feasibility of portable sources of $\bar{p}$'s - a sort of filling station approach. We indicate in the last column of Table II whether the experiment is considered suitable for a portable source.

We have summarized the physics case for proceeding with a Low Energy Antiproton Source in North America. In the opinion of the attendees at the workshop, this case is most alluring, having great potential for new and unexpected discoveries. The time is right for a push for a speedy construction of such a facility.

TABLE II. Characteristics of Low Energy $\bar{p}$ Experiments

Experiment	Difficulty*	No. $\bar{p}$'s req'd	Portable?
1 $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$, CP violation	Great	$>10^{14}$	No
2 K^0, $\bar{K}^0$ CP & T violation	High	$>10^{14}$	No
3 Inertial $M=\bar{M}$? CPT test	Low	Few	Yes
4 $\bar{H}^0$ spectra, Lamb, Ry? CPT	High	10^{12}	Yes
5 Gravity: $g(\bar{p}) = g(p)$?	High	10^{10}	Yes
6 Hadron Spectroscopy, exotica?	High	10^{12}	No
7 $\bar{p}$ - A Quark-Gluon Plasma	Low	10^{14}	No
8 $\bar{p}$ - A Strange Fireballs, etc	Low	10^{14}	No
9 Cold $\bar{H}$, $\bar{H}_2$, $\bar{H}^-$ prod^n & manip^n	High	few to $10^{\geq 12}$	Yes
10 Cold e^+ plasma + $\bar{p}$'s	High	few	Yes
11 Matter/AntiM Collision Dynamics	Low	$>10^6$	Yes
12 Condensed Matter Studies			
a $\bar{p}$ atoms	Low	10^6	Yes
b $\bar{p}$ channeling	Low	10^6	No?
c $\bar{p}$'s in dynamic traps	Great	10^6	Yes

*Definition of the different degrees of difficulty
Great = Don't Know How
High = We Know, But It's Hard
Low = State of the Art

X. REFERENCES

1 Proceedings of a Workshop on Physics at LEAR with Low-Energy Cooled Antiprotons (May. 1982. Erice). ed. U Gastaldi and R. Klapisch. (Plenum. New York. 1984)

2 Proceedings of a Workshop on Physics with Antiprotons at LEAR in the ACOL Era (January. 1985. Tignes). ed. U Gastaldi. R Klapisch. J M. Richard. and J. Tran Thanh Van. (Editons Frontieres. Gif sur Yvette. 1985)

3 Proceedings of the Workshop on the Design of a Low Energy Antimatter Facility (October. 1985. Madison). ed D Cline. (World Scientific. 1987)

4 Proceedings of the First Workshop on Antimatter Physics at Low Energy (April. 1986. Fermilab). ed. B E. Bonner and L S Pinsky. (FNAL Report. 1986)

5 J F Donoghue. p 241 of Ref. 4. J. F. Donoghue. B. R. Holstein. and G Valencia. Phys Letts B 178 (1986) 319.

6\. R L Jaffe. p. 1 of Ref 4. M. G. Olsson. p. 119 of Ref 4.

7 S. J Brodsky. G. P. Lepage. and S F. Tuan. Phys Rev. Letts. 59 (1987) 621

8 S R Sharpe. p 165 of Ref 4. and the present Proceedings

9 W R Gibbs. p 355 of Ref 4. D. Strottman and W R Gibbs. Phys Letts B 149 (1984) 288

10 PS200 at LEAR. "A Measurement of the Gravitational Acceleration of the Antiproton"

11 T Goldman and M. M Nieto. Phys Letts B 112 (1982) 437. T Goldman. R J Hughes. and M M Nieto. Phys Letts B 171 (1986) 217. also Phys. Rev D 36 (1987) 1254

12 R S Conti and A. Rich. p 97 of Ref 3

13 P B Schwinberg. R S Van Dyck. Jr. and H G. Dehmelt. Bull Am Phys Soc. 24 (1979) 1203: Phys. Rev Letts 47 (1981) 1679

14 CERN LEAR Experiment PS196. FNAL. Mainz. and U Washington

15 L Wolfenstein. p 227 of Ref 4

16 R K Adair. p 453 of Ref 2

17 P K Kabir Phys Rev D 2 (1970) 540

18 N W Tanner. p 483 of Ref 2

19 CERN LEAR Experiment PS195. also see the writeup by J Miller in

the present Proceedings for an excellent, detailed discussion of the physics of this experiment
20. CERN Courier, p 17, Oct. 1986
21 F. D Stacey, G. J Tuck, and G. I Moore, Phys Rev D 36, (1987). F D Stacey et al. Rev Mod Phys. 59 (1987) 157.
22 J. Rafelski, p 507 in Ref 1
23 B. I Deutch, et al. Phys Scr. T (to be published). see also p. 371 of Ref 4
24. H. Poth, p 325 in Ref. 4
25 J. B. A. Mitchell, in the present Proceedings
26. G. Gabrielse, et al., Phys Rev Lett 27 (1986) 2504
27 A. Rich, et al., in Proc. of the NATO Advanced Research Workshop on Atomic Physics with Positrons (in press).
28. C F Driscoll, p 184 in Ref 3
29. D. J Wineland and W. M Itano, Physics Today 40 (No 6), (1987) 34.
30. H Poth, Proc. of the Conference on the Intersections Between Particle and Nuclear Physics, AIP Conf Proc #150, e D F Geesaman (AIP, NY 1986) p 325.
31 M. S Chanowitz, p. 393 of Ref 4
32. E H Lieb, Rev. Mod Phys 48 (1976) 553
33 C W Clark, E Korevaar, and M G Littman, Phys Rev Lett 54, 320 (1985)
34 T H Braid, et al. Phys Rev B 19, 130 (1987)
35 C G Kuper, Phys Rev 122, 1007 (1961)
36 R. A. Ferrell, Phys. Rev 108, 167 (1957)
37 LEAR PS185, P D Barnes, et al., submitted to Phys Lett B, CERN preprint CERN-EP/87-153, 26 August 1987
38 P Lefevre, D Mohl, and D J Simon, p 69 in Ref 4